DC Voltage Interface Standards for Naval Applications

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***Abstract*—. MIL-STD-1399-300 and MIL-STD-1399-680 have established AC voltage interface requirements for U.S. naval surface ship electrical power systems. No such interface standards have been established for DC interfaces on U.S. naval surface ships. This paper provides recommendations for specific standard DC interface voltages for naval surface ship applications. These standard interface voltages are intended to facilitate the development and integration of DC loads.**

In recommending Interface Standards, the following were considered:

- **Existing commercial and military interface standards should be used to the maximum extent practical.**
- **Different standard voltage levels should differ significantly (greater than 25%)**
- **Higher voltages enable lower currents, and lighter cables.**
- **Standard voltage ratings of available semiconductor devices and insulation ratings should be considered.**

In addition to nominal voltage levels, power quality requirements and conformance testing requirements are recommended.

I. INTRODUCTION

Alternating Current (AC) has traditionally been employed for the generation, distribution, and utilization of electrical power onboard U.S. naval ships. The characteristics of the AC power interface between the power system and individual loads is defined in MIL-STD-1399-300 [1] for low voltages (below 1000 Volts) and MIL-STD-1399-680 [2] for high voltages (1000 Volts and above)

While the AC interfaces have historically enabled economical and reliable power systems, recent advances in power electronics facilitate cost-effective, power dense electrical equipment through the use of DC interfaces. Power systems employing DC interfaces can provide superior dynamic performance when confronted with high power dynamic loads.

These proposed standards are offered to the shipboard power system community (industry, academia, and government) for review, discussion and improvement. Eventually DC interfaces should be codified in an interface standard such as a new section of MIL-STD-1399. Standardizing DC nominal voltages and power quality will enable component and system developers to design DC equipment with confidence that these components and systems can be successfully integrated in future shipboard power systems.

The views expressed in this paper are those of the authors and do not reflect the official policy or position of the Department of the Navy, the Department of Defense, or the U.S. Government.

II. VOLTAGE SELECTION CRITERIA

In selecting standard nominal voltage values, the following criteria should be considered:

- Existing commercial and military interface standards should be used to the maximum extent practical.
- A significant difference (greater than 25%) should exist between different standard voltage levels.
- Higher voltages enable lower currents, and lighter cables.
- Standard voltage ratings of available semiconductor devices and insulation ratings should be considered.

Additionally, power quality requirements should be specified in a consistent manner where practical. For new standard interfaces, a common set of parameters should be employed.

Following the practice for AC systems, the interface between the power system and user equipment for non-pulse loads is at the point where the cable designations change from power system designations to other designations or no designation.

III. DEFINITIONS

The following definitions are used in describing the power quality requirements:

- Nominal System Voltage: The design system DC voltage. Used as a reference for establishing other power quality requirements.
- Steady State Voltage Tolerance (Power System Requirement): The allowable variation in the system DC voltage measured at the output of an

online source. This tolerance does not account for potential voltage loss in the distribution system.

- Maximum Voltage Ripple Amplitude: The root-mean-square voltage of the AC components of the voltage waveform. (Figure 1).
- Voltage Ripple Frequency: The frequencies comprising the AC component of the voltage waveform.
- Worst Case Voltage Offset from Positive Terminal to Ground: In the case that the Negative Terminal experiences a ground-fault, or in the case of a ground fault in a power source, the highest magnitude voltage with respect to ground expected on the Positive Terminal.
- Worst Case Voltage Offset from Negative Terminal to Ground: In the case that the Positive Terminal experiences a ground-fault, or in the case of a ground fault in a power source, the highest magnitude (negative) voltage with respect to ground expected on the Negative Terminal.
- Normal Service steady state voltage range (No damage to load, complete functionality of load): The range of steady state DC voltage that when applied to loads (with the maximum voltage ripple), the loads are expected to work properly. This range accounts for potential voltage drop in the distribution system as well as the steady-state voltage tolerance.
- Abnormal Service steady state voltage range (No damage to load, possible loss of functionality of load): The range of steady state DC voltage that when applied to the loads (with the maximum voltage ripple) does not result in damage to the load. The load may lose functionality as long as the loss of functionality does not directly result in damage to other equipment or injury to personnel.
- Voltage Transient Tolerance: Maximum permitted departure from the steady-state voltage during transient conditions for which the load must remain fully operational.

The relationships among the nominal system voltage, the steady state voltage tolerance, the normal and abnormal service steady state voltage ranges, and the impact of the Voltage Transient Tolerance are shown in Figure 2.

- Voltage Transient Recovery Time: The maximum time for the voltage waveform to return to the range specified by the normal service steady state voltage range and maximum voltage ripple amplitude. Characterized by the time constants associated with voltage regulation of the sources.
- Maximum Voltage Spike (normal operation) (Superimposed line to line and line to ground): The highest magnitude of a voltage spike between the positive terminal and the negative terminal, and each of the terminals and ground that when applied to the load or power system component, does not result in damage to the load or power system component and the load/power system component maintains complete functionality. Figure 3 is an example of a maximum voltage spike of 2500 volts for a 1000 VDC nominal voltage.
- Voltage Spike Waveform: A description of the shape of the voltage spike used in conjunction with the maximum voltage spike. See Figure 3 for an example from MIL-STD-1399 Section 300b.
- Maximum Load Line-to-Ground Capacitance: The maximum line to ground capacitance from each terminal of the load measured at 1 kHz.
- Minimum Load DC Resistance to Ground. The minimum DC resistance from each terminal of the load to ground.

The following definitions apply to non-pulse loads. A pulse load is any load that exceeds one or more of the following criteria:

- Maximum Load Current Ripple (Non-Pulse Loads): The magnitude of the AC components of the current waveform.
- Maximum Load Current Rate of Change (Non-Pulse Loads): The maximum rate of change of the current waveform for a load.
- Peak allowable In-Rush / Initialization Current (Non-Pulse Loads): The peak instantaneous current which flows upon energizing the load or part thereof.
- Peak in-rush Current Rate of Change (Non-Pulse Loads): The peak rate of change of in-rush current.

The following criteria apply to pulse loads:

- Maximum Power Ramp Rate: The maximum rate that a pulse load can increase or decrease its consumption of power from the power system. Operationally, a pulse power load may be commanded by the power system to use a lower level based on the configuration of the electric plant and state of charge of energy storage within the electric plant.
- Maximum Current: Pulse power loads must be able to control their maximum amount of current drawn from the power system. The specific value is established through the design of the power system and load. Operationally, a pulse power load may be commanded by the power system to limit its current draw to a lower value based on the configuration of the electric plant and state of energy storage within the electric plant.
- Pulse Width: Specified as a range (minimum and maximum) of time that a pulse falls outside of the non-pulse limits. The specific values are established through the design of the power system and load. Operationally, a pulse power load may be commanded by the power system to use only a portion of this range.
- Pulse Recovery Time: Specified as a minimum time after a pulse has ended before another pulse

may be applied. The specific value is established through the design of the power system and load. Operationally, a pulse power load may be commanded by the power system to use a larger Pulse Recovery Time.

Note that sources are required to provide power of a higher quality than what is required for loads to operate satisfactorily. This accounts for degradation of power quality in the distribution system, manufacturing tolerances, and equipment degradation over time. This practice helps ensure a reliable power system design.

If specified, control interfaces must be established between loads and the power management system. The control interface includes message formats, communications protocols and interfaces, and the expected behavior of the load and power system with respect to the messages. The control interface requirements may differ for pulse loads and non-pulse loads. Control interfaces will need to comply with evolving DOD and NAVSEA direction on Cybersecurity.

For pulse loads the cable between the load and the first component of the distribution system (power conversion equipment or switchgear) may have a length limit to prevent excessive voltage drop due to the cable inductance when subjected to a high power ramp rate. It may prove economically advantageous to define this cable as part of the pulse power load and design the load equipment to accept a larger voltage drop than specified via the Worst Case Voltage Transient Excursion.

System stability must be designed from a system perspective. Acquisition documentation must define both Power System Source Impedance and Load Impedance to ensure overall system stability. It may prove beneficial to define a control system interface whereby the Load Impedance of specific loads may be negotiated between the power system and the load.

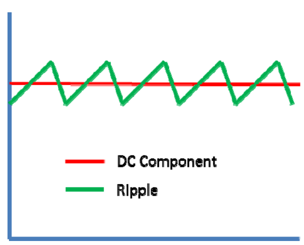

Figure 1: Waveform Example

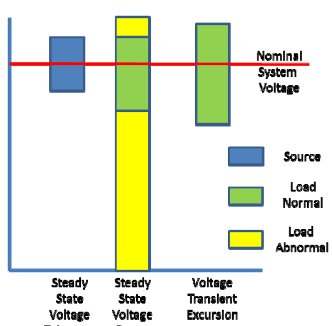

Figure 2: Relationship of Voltage Ranges

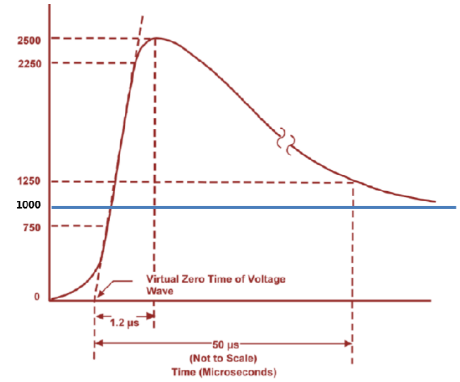

Figure 3: Voltage Spike Example (1000 VDC nominal, 2500 V Maximum Voltage Spike)

IV. DISCUSSION OF LOAD DEFINITIONS

As used within naval electric power systems, [1] and [2] define a “pulse”, “pulsed load” and “ramp load”. The definitions in [1] and [2] derive from the technologies prevalent when [1] was initially drafted, AC electromechanical analog technologies. The proliferation of power electronic converters has overtaken the definitions in [1] and [2]. In [1] and [2], a “pulse” is a singular (non-recurring) brief excursion of power longer than 1 cycle (16.7ms in 60Hz AC systems) and less than 10s. The magnitude of the excursion is not characterized. Presumably, the excursion is applied rapidly and removed rapidly. In [1] and [2], a “pulse load” is a frequent or regularly “repeated” power excursion. Sonar and radar are cited as examples of this type of power user. The magnitude of the pulse is presumably uniform. In [1] and [2], a “ramp load” is defined as being applied smoothly; is “continuously” in the mathematical sense implied here? A “step load” is not defined in [1] and [2]. While an “ideal step load” is not possible in a system with any inductance, with power electronic converters, power users can turn on very rapidly, effectively a “step load.” Power users can also very rapidly change the amount of power they draw, a “step change in load.”

Why is characterizing how power users draw power important? Interface standards operate on the premise that the electric power system, in this case, will provide electric power in conformance with the system characteristics given in the interface standard if all of the power users draw power in accordance with the load constraints given in the interface standard. These load constraints are articulated using the load definitions discussed herein. Were a significant power system user to draw energy too rapidly from the power system, the power system would be unable to maintain voltage et cetera; then, all of the power users would be negatively affected. The objective in this discussion is to describe the power user energy draw in such a way that reasonable limits can be identified, limits within which the power system can provide energy while supplying quality power, and limits within which the power users can operate satisfactorily. What must be done is to describe, in terms relevant today, the rate of energy extraction/provision to base DC interface standards upon.

Here, we focus on “step loads” and “step changes in load”; “step” implies very rapidly applied or removal of power draw.

A "pulse", therefore, is comprised perhaps of two "step changes in load", a "step" increase in power draw and soon thereafter a "step" decrease in power draw. Heretofore, the limit on a "step" change by a power user was given as a percentage of the supplying generator rating, the specific percentage was a function of the power users' power factor (a distinctly AC concept). How to determine the power user load constraint, the limit, for a "step" change in power draw in a DC electric power system is an open challenge.

It is also important to focus on the power users most likely to challenge the electric power system performance. When imposing "ramp load" or other energy extraction/provision constraints on power users, the maximum power draw of the power user is a criterion. Power users below some threshold in kW, threshold based upon system capacity, need not be so constrained. How to determine the maximum power draw threshold is an open challenge.

V. LOW VOLTAGE RECOMMENDATIONS

The following DC voltages are recommended for DC load utilization:

- 155 V
- 375 V
- 650 V

These nominal voltages are based on existing equipment onboard submarines (155 V) and DDG 1000 (375 V and 650 V).

A shipboard power system may be required to provide DC power to vehicle (aircraft, unmanned vehicle, or watercraft) equipment or shipboard equipment developed for vehicle applications. In addition to the other voltages recommended above, shipboard power systems may include power interfaces at the following voltages:

- 28 V
- 270 V

The Littoral Combat Ship (LCS) Interface Control Document (ICD) for example, includes a 28 V interface to containers.

To help ensure system stability, the capacitance measured from each terminal to ground should be matched to within 10% of each other.

A. 155 V Interface

MIL-STD-1399 section 390 [6] defines a 155 V interface for submarine applications. The authors propose extending applicability of MIL-STD-1399 section 390 to include surface ships. Note that a number of "universal" switched mode power supplies designed for AC operation between 50 and 60 Hz and from 90 to 240 VAC also can operate on 155 VDC. Employing two 155 VDC sources connected via diodes (termed auctioneering diodes) for these loads is an inexpensive method for providing un-interruptible power.

B. 375 V Interface

Table 1 provides the proposed power quality interface requirements between the power system and the load for the 375 V DC interface. Note that the source may have to regulate the voltage within a tighter tolerance to account for voltage drop in the distribution system. These interface requirements are based in part on ETSI EN 300 132-3-1 [7] and on previous naval procurements for the DDG 1000. The 375 V interface should generally be limited to loads less than about 100 kW

For pulse loads, the duty cycle, ramp rates, and peak currents must be negotiated in operation through a control interface between the load and the power management system. The load may not violate the non-pulse load requirements without first gaining concurrence from the power management system. Synchronization of the pulse application by the load and power system dynamics may be required via the control interface.

650 V InterfaceTable 2 provides the proposed power quality interface requirements between the power system and the load for the 650 V DC interface. Note that the source may have to regulate the voltage within a tighter tolerance to account for voltage drop in the distribution system. These interface requirements are based on previous navy procurements for the DDG 1000. The 650 V interface should generally be limited to loads greater than 15 kW and less than 450 kW.

For pulse loads, the duty cycle, ramp rates, and peak currents must be negotiated in operation through a control interface between the load and the power management system. The load may not violate the non-pulse load requirements without first gaining concurrence from the power management system. Synchronization of the pulse application by the load and power system dynamics may be required via the control interface.

Table 1: 375 V DC Power Quality

Characteristic	Value
Nominal System Voltage	375 VDC
Steady State Voltage Tolerance (Power System Requirement)	±4%
Maximum Voltage Ripple Amplitude	1.5% Vrms
Voltage Ripple Frequency	Frequency of Largest Component of Voltage Ripple is less than 10 kHz.
Worst Case Voltage Offset from Positive Terminal to Ground	+ 395 VDC
Worst Case Voltage Offset from	- 395 VDC

Negative Terminal to Ground		
Normal Service steady state voltage range (No damage to load, complete functionality of load)	±5%	
Abnormal Service steady state voltage range (No damage to load, possible loss of functionality of load)	0 to 95% and 105% to 110%	
Voltage transient tolerance (No damage to load, complete functionality of load)	±8.5%	
Voltage Transient Recovery Time	250 ms	
Maximum Voltage Spike (normal operation)	750 V	
Voltage Spike Waveform (see MIL-STD-1399-300B figure 6)	1.2 μs x 50 μs	
Maximum Regenerative Power	0 kW	
Maximum Load Line-to-Ground Capacitance	.005 μF per kW measured at 1 kHz	
Minimum Load DC Resistance to Ground	10 MΩ	
Maximum Load Current Ripple (Non-Pulse Loads)	CE101 limit for submarine applications, DC from MIL-STD-461F	
Maximum Load Current Rate of Change (Non-Pulse Loads)	Nominal Rated Load Current (A)	Maximum Rate of Change (A/ms)
	≤ 186	30
	> 186 and ≤ 371	58
	> 371	125
Peak allowable In-Rush / Initialization Current (Non-Pulse Loads)	Equipment Rated Load (kW)	Multiplier of Rated Current
	< 15	10
	≥ 15 and ≤ 30	6
	> 30 and ≤ 50	4
	> 50	2
Peak In-rush Current Rate of Change (Non-Pulse Loads)	Nominal Rated Load Current (A)	Maximum Rate of Change (A/ms)
	≤ 186	60
	> 186 and ≤ 371	115
	> 371	250
Control Interface (pulse loads)	See Text	
Control Interface (non-pulse loads)	As specified in Acquisition Documentation	
Maximum Power Ramp Rate (pulse loads)	150 MW/s	
Maximum Current (pulse loads)	As specified in Acquisition Documentation	
Pulse width (pulse loads)	As specified in Acquisition Documentation	
Pulse Recovery Time (pulse loads)	As specified in Acquisition Documentation	
Power System Source Impedance	As specified in Acquisition Documentation	
Load Impedance	As specified in Acquisition Documentation	

Table 2: 650 V DC Power Quality

Characteristic	Value	
Nominal System Voltage	650 VDC	
Steady State Voltage Tolerance (Power System Requirement)	± 4%	
Voltage Ripple Amplitude	1.5% Vrms	
Voltage Ripple Frequency	Largest Component of Voltage Ripple Frequency is less than 10 kHz.	
Worst Case Voltage Offset from Positive Terminal to Ground	675 VDC	
Worst Case Voltage Offset from Negative Terminal to Ground	- 675 VDC	
Normal Service steady state voltage range (No damage to load, complete functionality of load)	± 5%	
Abnormal Service steady state voltage range (No damage to load, possible loss of functionality of load)	0 to 95% and 105% to 110% VDC	
Voltage transient tolerance (No damage to load, complete functionality of load)	±8.5%	
Voltage Transient Recovery Time	250 ms	
Maximum Voltage Spike (normal operation)	1300 V	
Voltage Spike Waveform (see MIL-STD-1399-300B figure 6)	1.2 μs x 50 μs	
Maximum Regenerative Power	0 kW	
Maximum Load Line-to-Ground Capacitance	.005 μF per kW measured at 1 kHz	
Minimum Load DC Resistance to Ground	10 MΩ	
Maximum Load Current Ripple (Non-pulse Loads)	CE101 limit for submarine applications, DC from MIL-STD-461F	
Maximum Load Current Rate of Change (Non-Pulse Loads)	Nominal Rated Load Current (A)	Maximum Rate of Change (A/ms)

	≤ 186	30
	> 186 and ≤ 371	58
	> 371	300
Peak allowable In-Rush / Initialization Current (Non-Pulse Loads)	Equipment Rated Load (kW)	Multiplier of Rated Current
	< 50	10
	≥ 50 and ≤ 100	6
	> 100 and ≤ 175	4
	> 175	2
Peak In-rush Current Rate of Change (Non-Pulse Loads)	Nominal Rated Load Current (A)	Maximum Rate of Change (A/ms)
	≤ 186	60
	> 186 and ≤ 371	115
	> 371	300
Control Interface (pulse loads)	See Text	
Control Interface (non-pulse loads)	As specified in Acquisition Documentation	
Maximum Power Ramp Rate (pulse loads)	260 MW/s	
Maximum Current (pulse loads)	As specified in Acquisition Documentation	
Pulse width (pulse loads)	As specified in Acquisition Documentation	
Pulse Recovery Time (pulse loads)	As specified in Acquisition Documentation	
Power System Source Impedance	As specified in Acquisition Documentation	
Load Impedance	As specified in Acquisition Documentation	

C. 28 and 270 V Interface

MIL-STD-704 [8] defines 28 V and 270 V interfaces for aircraft. The authors propose extending applicability of MIL-STD-704 to include surface ship interfaces to vehicle (aircraft, unmanned vehicle, or watercraft) equipment, shipboard equipment developed for vehicle applications, and containers such as those used on the LCS.

VI. HIGH VOLTAGE RECOMMENDATIONS

The following nominal DC voltage is recommended for intra-zone power distribution and load utilization:

- 1 kV

The following nominal DC voltages are recommended for inter-zone power distribution and load utilization:

- 6 kV
- 12 kV
- 18 kV

A number of voltage levels between 650 V and 1 kV have been employed within the Navy and industry for a variety of applications. Systems employing nominal DC voltages of 700, 750, 800, 950, and 1000 can be found in defense, transportation, photovoltaic, and process control applications.

A number of power module manufacturers offer affordable IGBT modules with a voltage rating of 1700 volts. A nominal voltage of 1000 V is an upper bound for reliable operation of these devices. The commercial market for these devices is growing with the increased employment of 1 kV photovoltaic systems in Europe and North America.

The authors recommend 1 kV to maintain alignment with the commercial practice with photovoltaic systems and to minimize conductor size. 1 kV has also been used in several naval applications.

For naval applications, NSTM chapter 300 [3] requires additional maintenance personnel safeguards for systems with nominal voltages of 1000 Volts or higher as compared to systems with lower nominal voltages. There is a temptation to choose a slightly lower nominal voltage, say 950 as a standard, to avoid the additional safeguards. The authors contend that choosing a minimally lower voltage to avoid increased safeguards does not serve the sailor well. A 1000 V nominal system and a 950 V nominal system present essentially the same hazard to the sailor. The authors recommend the NSTM chapter 300 safety requirements for a nominal 1000 volt system be compared with commercial practice as defined in NFPA 70e [4]; differences should be rationalized. If warranted, NSTM chapter 300 should be modified.

The three higher voltages are preferred rated voltages listed in IEEE Std 1709^{TM}-2010 [5]. For the same transfer of power, the conductor size for 6 kV DC is less than that required for 4160 VAC. Similarly the conductor size for 18 kV is less than that required for 13800 VAC.

To help ensure system stability, the capacitance measured from each terminal to ground should be matched to within 10% of each other.

A. 1 kV Interfaces

Table 3 provides the proposed power interface for 1 kV power interfaces. Note that the source may have to regulate the voltage within a tighter tolerance to account for voltage drop in the distribution system. These interfaces are based on ongoing Navy procurements. The 1 kV interface should generally be limited to loads above about 100 kW and less than 3 MW.

For pulse loads, the Maximum Power Ramp Rate, Maximum Current, Pulse Width, and Pulse Recovery Time must be negotiated in operation through a control interface between the load and the power management system. The load may not violate the non-pulse load requirements without first gaining concurrence from the power management system. Synchronization of the pulse application by the load and power system dynamics may be required via the control interface.

B. 6, 12, and 18 kV Interfaces

Table 4 provides the proposed power interface for 6, 12, and 18 kV power interfaces. Note that the source may have to regulate the voltage within a tighter tolerance to account for voltage drop in the distribution system. These interfaces are inspired by IEEE Std 1709™-2010.

For pulse loads, the duty cycle, ramp rates, and peak currents must be negotiated in operation through a control interface between the load and the power management system. The load may not violate the non-pulse load requirements without first gaining concurrence from the power management system. Synchronization of the pulse application by the load and power system dynamics may be required via the control interface.

Additional investigation and research are required to properly specify the Maximum Load Line-to-Ground Capacitance.

Table 3: 1 kV Power Quality

Characteristic	Value
Nominal System Voltage	1000 VDC
Steady State Voltage Tolerance (Power System Requirement)	960 to 1040 VDC
Maximum Voltage Ripple Amplitude	25 Vrms
Voltage Ripple Frequency	Frequency of Largest Component of Voltage Ripple is less than 10 kHz.
Worst Case Voltage Offset from Positive Terminal to Ground	+ 1050 VDC
Worst Case Voltage Offset from Negative Terminal to Ground	- 1050 VDC
Normal Service steady state voltage range (No damage to load, complete functionality of load)	950 to 1050 VDC
Abnormal Service steady state voltage range (No damage to load, possible loss of functionality of load)	0 to 950 VDC and 1050 to 1150 VDC
Voltage transient tolerance (No damage to load, complete functionality of load)	±85 V
Voltage Transient Recovery Time	< 0.5 s max
Maximum Voltage Spike (normal operation) (superimposed line to line and line to ground)	2000 V peak
Voltage Spike Waveform (see MIL-STD-1399-300B figure 6)	1.2 μs x 50 μs
Maximum Load Line-to-Ground Capacitance	< 0.005 μF per kW measured at 1 kHz
Minimum Load DC Resistance to Ground	10 MΩ
Maximum Load Current Ripple (Non-Pulse Loads)	CE101 limit for submarine applications, DC from MIL-STD-461F
Maximum Load Current Rate of Change (Non-Pulse loads)	2 A/ms
Peak allowable In-Rush / Initialization Current (Non-Pulse Loads)	2 times Rated Load Current (A)
Peak In-rush Current Rate of Change (Non-Pulse Loads)	2.5 A/ms
Maximum Power Ramp Rate (pulse loads)	400 MW/s
Maximum Current (pulse loads)	As specified in Acquisition Documentation
Pulse width (pulse loads)	As specified in Acquisition Documentation
Pulse Recovery Time (pulse loads)	As specified in Acquisition Documentation
Control Interface (pulse loads)	See Text
Control Interface (non-pulse loads)	As specified in Acquisition Documentation
Power System Source Impedance	As specified in Acquisition Documentation
Load Impedance	As specified in Acquisition Documentation

Table 4: 6 kV, 12 kV, and 18 kV Power Quality

Characteristic	Value
Nominal System Voltage	6,000 / 12,000 / 18,000 VDC
Steady State Voltage Tolerance (Power System Requirement)	±10%
Maximum Voltage Ripple Amplitude	3.5% rms
Voltage Ripple Frequency	Frequency of Largest Component of Voltage Ripple is less than 10 kHz.
Worst Case Voltage Offset from Positive Terminal to Ground	+ 110%
Worst Case Voltage Offset from Negative Terminal to Ground	- 110%
Normal Service steady state voltage range (No damage to load, complete functionality of load)	-16% +11%
Abnormal Service steady state voltage range (No damage to load, possible loss of functionality of load)	0 to 84% and 111% to 115%
Voltage transient tolerance	±8.0%

(No damage to load, complete functionality of load) Voltage Transient Recovery Time	500 ms
Maximum Voltage Spike (normal operation) (Line to Line and Line to Ground)	2 times nominal voltage
Voltage Spike Waveform (see MIL-STD-1399-300B figure 6)	1.2 μs x 50 μs
Maximum Load Line-to-Ground Capacitance	As specified in Acquisition Documentation
Minimum Load DC Resistance to Ground	1200 kΩ / 2400 kΩ / 3600 kΩ
Maximum Load Current Ripple (Non-Pulse Loads)	CE101 limit for submarine applications, DC from MIL-STD-461F
Maximum Load Current Rate of Change (Non-Pulse loads)	2 A/ms
Peak allowable In-Rush / Initialization Current (Non-Pulse Loads)	1.5 times Rated Load Current (A)
Peak In-rush Current Rate of Change (Non-Pulse Loads)	3 A/ms
Control Interface (pulse loads)	See Text
Control Interface (non-pulse loads)	As specified in Acquisition Documentation
Maximum Power Ramp Rate (pulse loads)	400 MW/s
Maximum Current (pulse loads)	As specified in Acquisition Documentation
Pulse width (pulse loads)	As specified in Acquisition Documentation
Pulse Recovery Time (pulse loads)	As specified in Acquisition Documentation
Power System Source Impedance	As specified in Acquisition Documentation
Load Impedance	As specified in Acquisition Documentation

VII. COMPLIANCE TESTING

A new DC interface standard will require details on compliance testing. Anticipated required tests include:

- Load Characterization Measurements
  - Line to Ground Capacitance
  - DC Resistance to Ground
  - Current Ripple
  - Load Current Rate of Change (non-pulse)
  - In-Rush / Initialization Current (non-pulse)
  - Peak In-rush Current Rate of Change (non-pulse)
  - Load Impedance
- Susceptibility Tests
  - Voltage Tolerance
  - Voltage Transient
  - Voltage Ripple
  - Voltage Spike
  - Voltage Offset Tests (terminal to ground)
  - Abnormal Service Steady Stage Voltage
- Pulse Load Tests (if applicable)
  - Control Interface Operability
  - Power Ramp Rate
  - Maximum Current
  - Pulse Width
  - Pulse Recovery Time

In developing the requirements for these tests, emphasis should be placed at minimizing the cost of conducting the tests while still assuring the equipment will work properly and safely in a shipboard environment.

These tests are only intended to verify compliance with the power quality requirements defined in the interface specification. Additional testing will likely be required for DC equipment to verify Electromagnetic Interference (EMI) requirements and stray DC field requirements are met. Equipment requirements are detailed in MIL-DTL-917.

VIII. CONCLUSIONS

This paper has proposed standard DC nominal voltages and associated power quality parameters for naval ships. The authors recommend these proposed standards be reviewed and improved by the shipboard power system community (industry, academia, and government) before being codified in an interface standard such as a new section of MIL-STD-1399. By standardizing DC nominal voltages and power quality, component and system developers can develop DC equipment with confidence that these components and systems can be successfully integrated in future shipboard power systems.

REFERENCES

[1] Department of Defense, " Electric Power, Alternating Current," MIL-STD-1399 Section 300B, 21 April 2008.

[2] Department of Defense, "High Voltage Electric Power, Alternating Current," MIL-STD-1399 Section 680, 14 April 2008.

[3] Naval Sea Systems Command (NSTM 300), "Naval Ship's Technical Manual Chapter 300 Electric Plant – General," S9086-KC-STM-010 Revision 9, 1 May 2012. (Limited Distribution)

[4] National Fire Protection Association (NFPA 70E), "Standard for Electrical Safety in the Workplace," 2015.

[5] IEEE, "Recommended Practice for 1 kV to 35 kV Medium-Voltage DC Power Systems on Ships," IEEE Std 1709™-2010, 2 November 2010.

[6] Department of Defense,"Electric Power, Direct Current, (Other than Ship's Battery) for Submarines," MIL-STD-1399 Section 390, 2 October 1987.

[7] ETSI, "Environmental Engineering (EE); Power supply interface at the input to telecommunications and datacom (ICT) equipment; Part 3: Operated by rectified current source, alternating current source or direct current source up to 400 V; Sub-part 1: Direct Current source up to 400 V," V2.1.1 of October 2011.

[8] Department of Defense, "Aircraft Electric Power Characteristics," MIL-STD-704F, 12 March 2004.

[9] Department of Defense, "Detail Specification Electric Power Equipment, Basic Requirements for," MIL-DTL-917F of 5 August 2014.